Activation of Mg-doped GaN by Thermal Annealing in Oxidizing Atmosphere

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GaN and related materials have attracted much attention because of the excellent optical properties which are suitable for the devices such as blue/ultra-violet light-emitting diode (LED) or laser diode (LD). Recently, these devices have been successfully produced, but the carrier concentration of the p-type layer is still low, resulting in the increase of the operation voltage. Since Mg acceptors in GaN are considered to be passivated by hydrogen during metal organic chemical vapor deposition (MOCVD) growth [1], the as-grown layer is usually activated by thermal annealing at above 700℃ in N_2 ambient [2] to break the Mg-H bonds. Although these methods have been widely used, it is not easy to obtain the sample with a carrier concentration higher than 1×10^{18} cm^{-3}. In addition, heavy doping of the acceptor impurities and/or increase of annealing temperature often cause degradation in crystalline quality, consequently resulting in low hole concentration by the compensate effect [3]. Therefore, it is of great interest to find a new method for activation. Brandt *et al*. obtained high-quality cubic p-type GaN samples on GaAs (113) substrates using molecular beam epitaxy (MBE) by co-doping method [4], in which a carrier concentration of 5×10^{18} cm^{-3} was achieved. Recently, Koide *et al*. found that oxygen reduces contact resistance and sheet resistance during alloying processes for a metal contact on p-GaN [5]. More recently, Hull *et al.* investigated the influence of oxygen during annealing on activation process [6]. They found from secondary ion mass spectroscopy (SIMS) measurement that oxygen enhances the out-diffusion of hydrogen, which results in activation at lower temperatures. Although several studies on the effect of oxygen on activation process have been done, the activation mechanism from semi-insulating (SI) to p-type has not been clarified yet. In order to solve these problems, we have investigated the activation processes for Mg-doped GaN samples by thermal annealing using O_3 and N_2O, and compared it with the annealing in O_2 and N_2.

The samples used in this study were grown with MOCVD. Mg-doped GaN layers with a thickness of 1.5 μm were grown on a 2-inch sapphire (0001) substrate using a low-temperature buffer layer technique. As-grown samples were cut from the same wafer with the size of 6mm×6mm, cleaned in an ethanol ultrasonic bath for 3 min, and introduced into a quartz tube furnace for annealing at various temperatures in different gases for 10 min. The annealing gases investigated in this study were $1.5\%O_3+98.5\%O_2$, $100\%N_2O$, $67\%N_2+33\%O_2$, and $100\%N_2$. After the annealing processes, all samples were cleaned in 36% HCl for 30 min at room temperature to remove native oxides, rinsed in deionized (DI) water for 1 min, and dried by N_2 blower. Ni electrodes were deposited by thermal evaporation through a mask, then annealed in the same quartz tube furnace in N_2 at 550℃ for 10min to make alloy for ohmic contacts. Temperature-dependent Hall effect measurements were carried out by the van der Pauw technique. SIMS measurements were done to observe the change of the hydrogen concentration in bulk GaN.

Figure 1 shows the carrier concentration of each sample annealed in various gases at different temperatures. It is confirmed that the carrier concentration curves for $1.5\%O_3$ and N_2O shift toward lower

temperature by approximately 100K. The carrier concentration of the samples annealed in 1.5%O_3 or N_2O reached to the order of 10^{17} cm^{-3} when it was annealed at above 550℃. These results indicate that oxidizing atmosphere helps acceptors to be activated. Furthermore, the carrier concentrations of the samples annealed in 67%N_2+33%O_2 at 600℃ and 800℃ were almost the same as those of the samples annealed in 1.5%O_3 or N_2O. These results indicate that the difference of oxygen concentration in the atmosphere and oxidizability are not important factors to lower the activation temperature. Figure 2 shows Arrhenius plots of the carrier concentrations for the samples annealed in 1.5%O_3, in N_2O, and in N_2. Taking the dispersion of data points into account, we concluded that there is no atmosphere dependence in the activation energies. These results indicate that the annealing atmosphere does not affect the character of the acceptor level.

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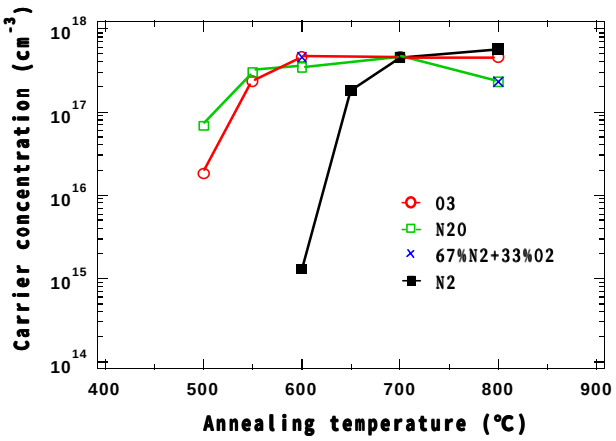

Fig. 1. Annealing temperature dependence of the carrier concentrations for each sample annealed in various atmospheres. Hall effect measurements were carried out at room temperature.

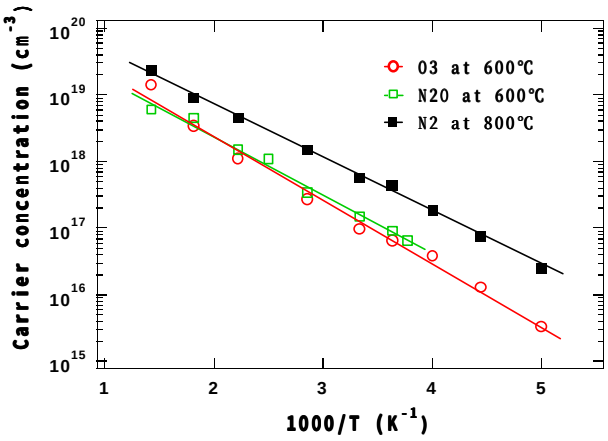

Fig. 2. Arrhenius plots of the carrier concentration of each sample. The samples were annealed in 1.5%O_3, in N_2O, and in N_2.